Inclusive jet production in electron-nucleon collisions

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Based on G. Abelof, R. Boughezal, X. Liu, FP
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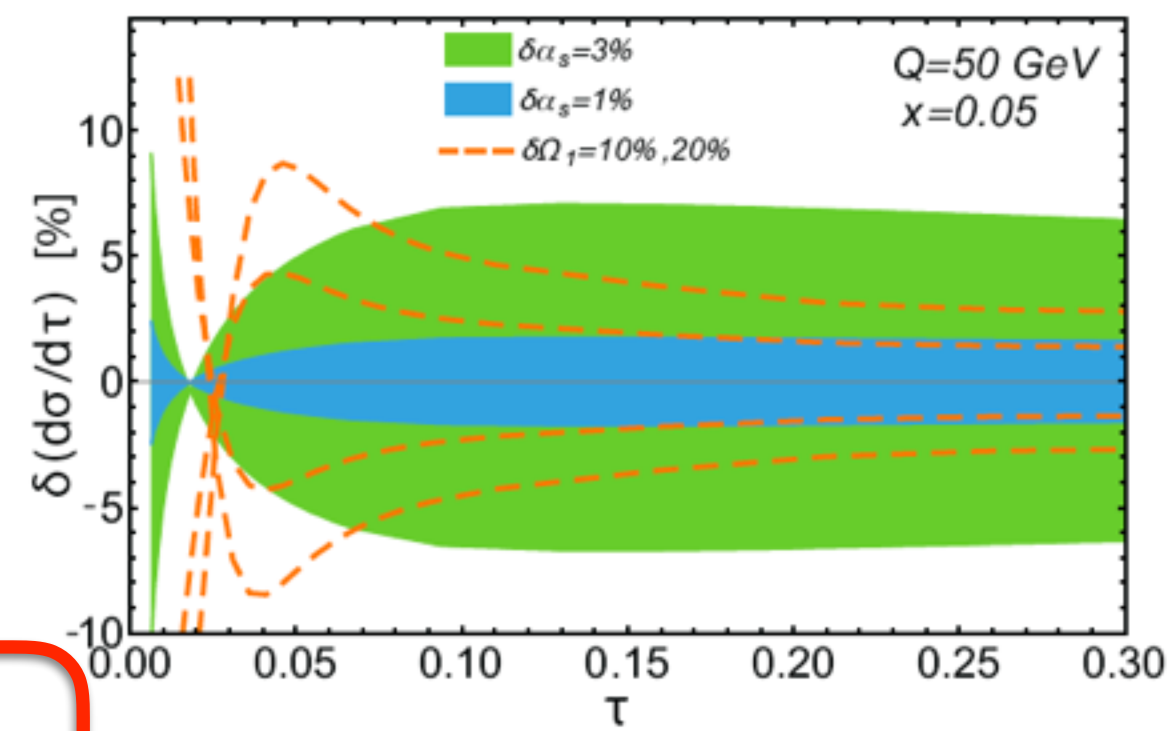
Jet physics at the EIC

- Numerous physics motivations for studying jet production at a future EIC

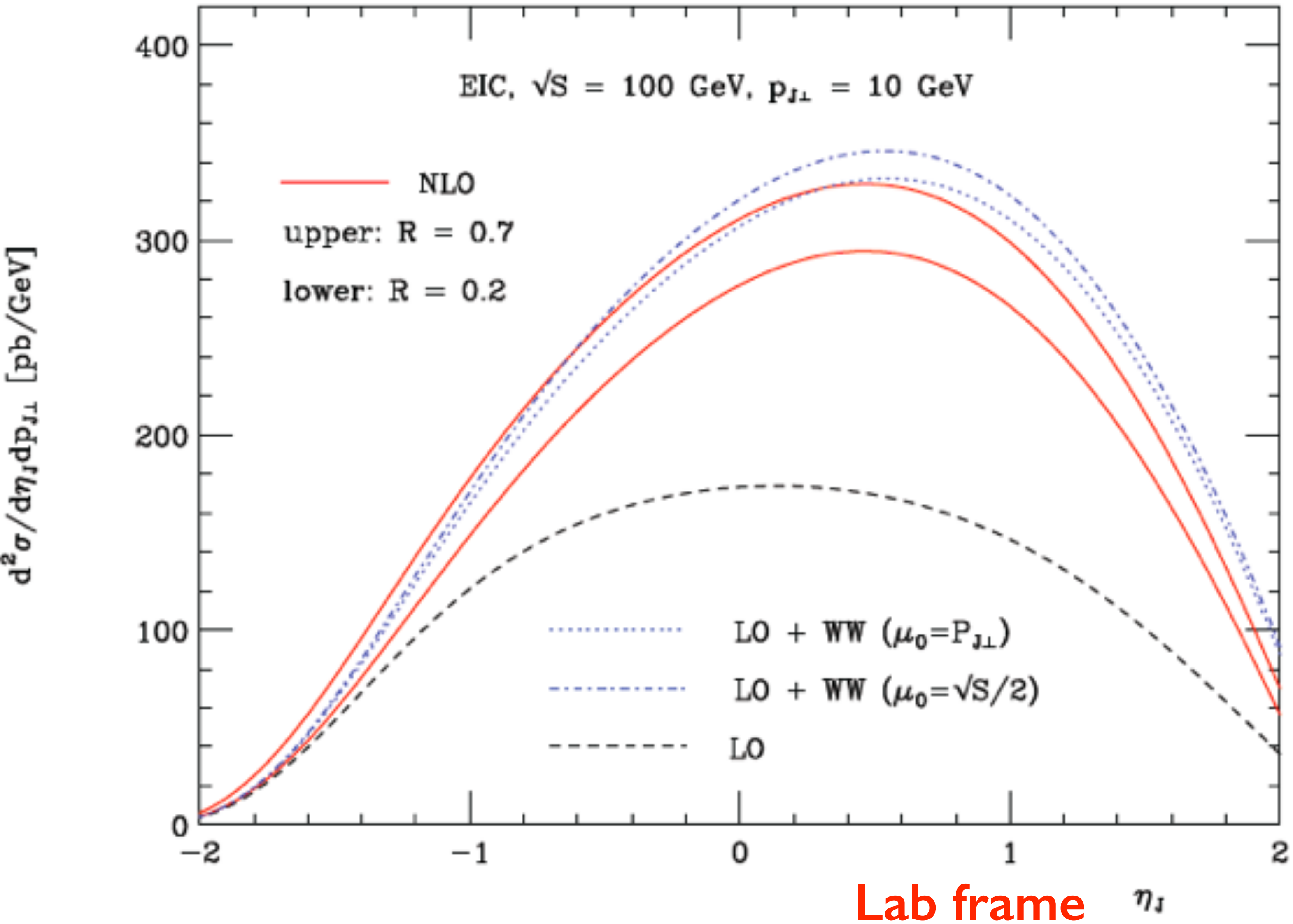
- Measurement of the strong coupling constant D. Kang, Lee, Stewart (2013)
- Determination of higher-twist properties of the proton Z. Kang, Metz, Qiu, Zhou (2011)
- Determination of parton distribution functions
- Measure properties of the nuclear medium with event shapes Z. Kang, Liu, Mantry, Qiu (2012)



The precision of an EIC plays a critical role in all of these measurements!

The challenge: large corrections

Hinderer, Schlegel, Vogelsang (2015)



Lab frame

- Large NLO perturbative corrections, O(100%)
- Important, but not dominant, corrections from photon-initiated processes
- Does the perturbative series converge at NNLO?
- Are the NNLO corrections dominated by a single channel?

Goals:

- Investigate the NNLO corrections to EIC jet production for its intrinsic interest
- Show that techniques for LHC calculations can also enable precision EIC studies

Definition of the process

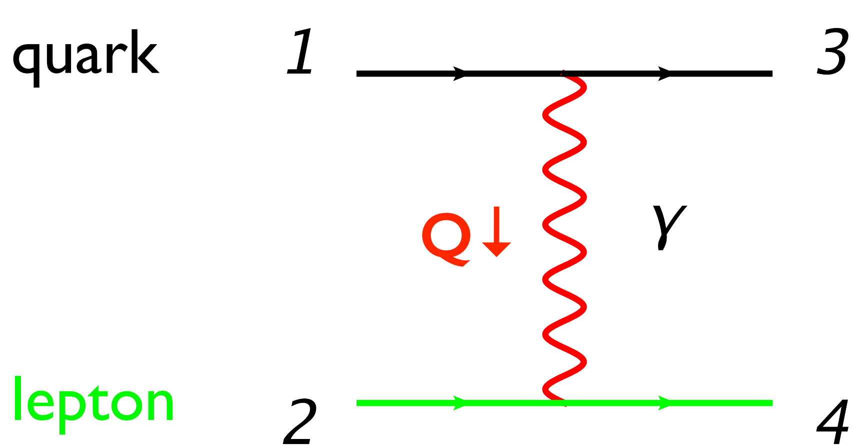
DIS: $eN \to eN$

- lepton tagged
- Cut on Q^2
- hard scale: Q

Inclusive jet production: $eN \to jX$

- lepton *not* tagged
- Cut on p_{Tjet}
- hard scale: p_{Tjet}

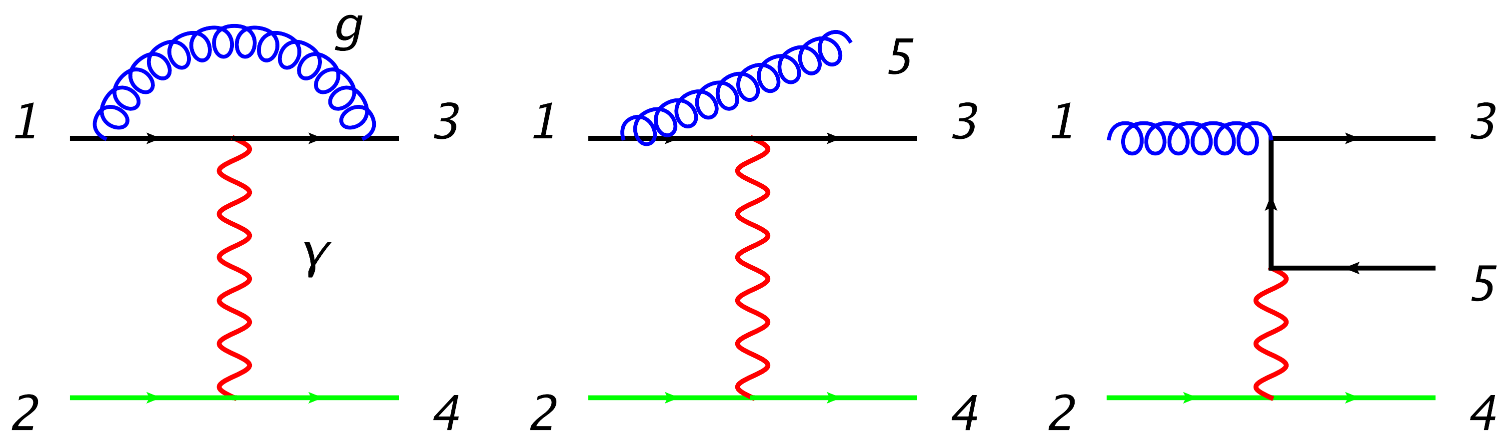
$$q(p_1)+l(p_2) \to q(p_3)+l(p_4)$$



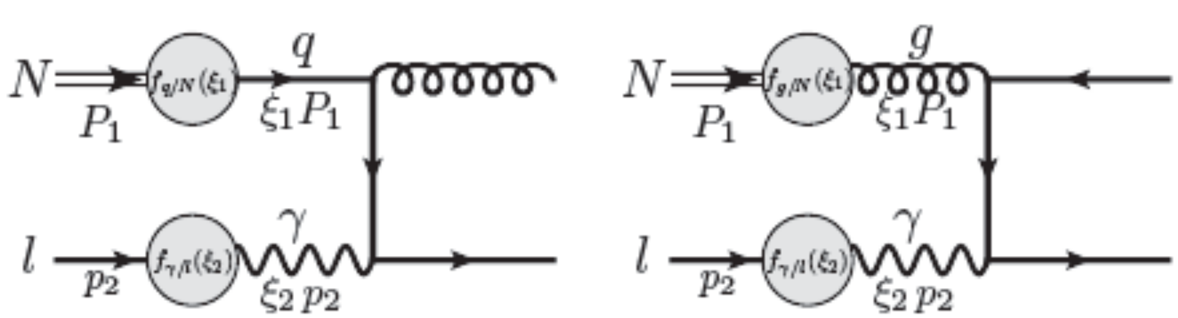
- **Leading order**: identical for both processes, lepton recoils against a jet

NLO O($\alpha^2\alpha_S$) corrections

- Typical real and virtual corrections to the quark-lepton scattering processes; new contribution from gluon-lepton scattering→ calculation amenable to standard techniques



- New configuration: lepton collinear to the beam (Q^2~0), with two jets balancing in the transverse plane; on-shell photon scattering with quark→differentiates DIS and inclusive jet production

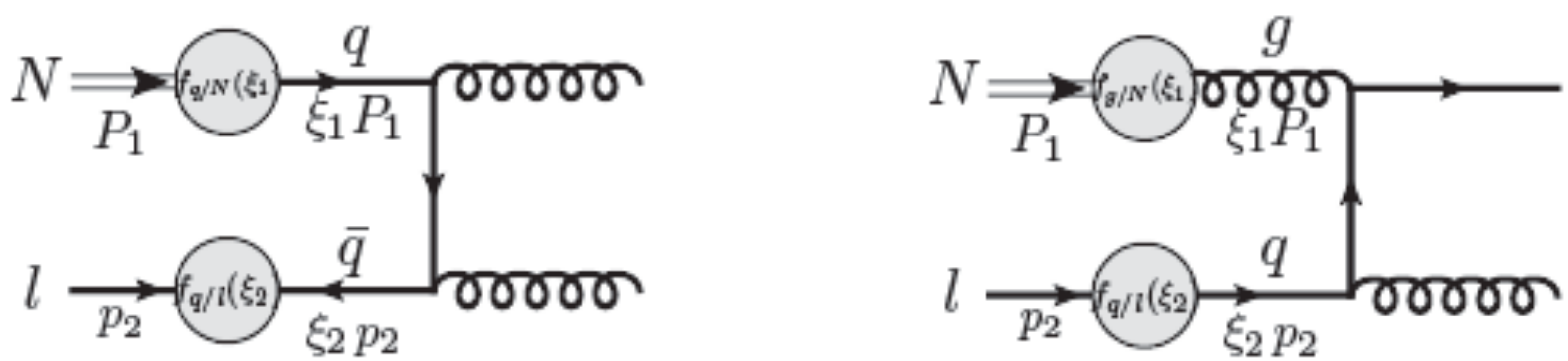


$$f_{\gamma/l}(\xi) = \frac{\alpha}{2\pi} P_{\gamma l}(\xi) \left[\ln\left(\frac{\mu^2}{\xi^2 m_l^2} \right) - 1 \right] + \mathcal{O}(\alpha^2)$$

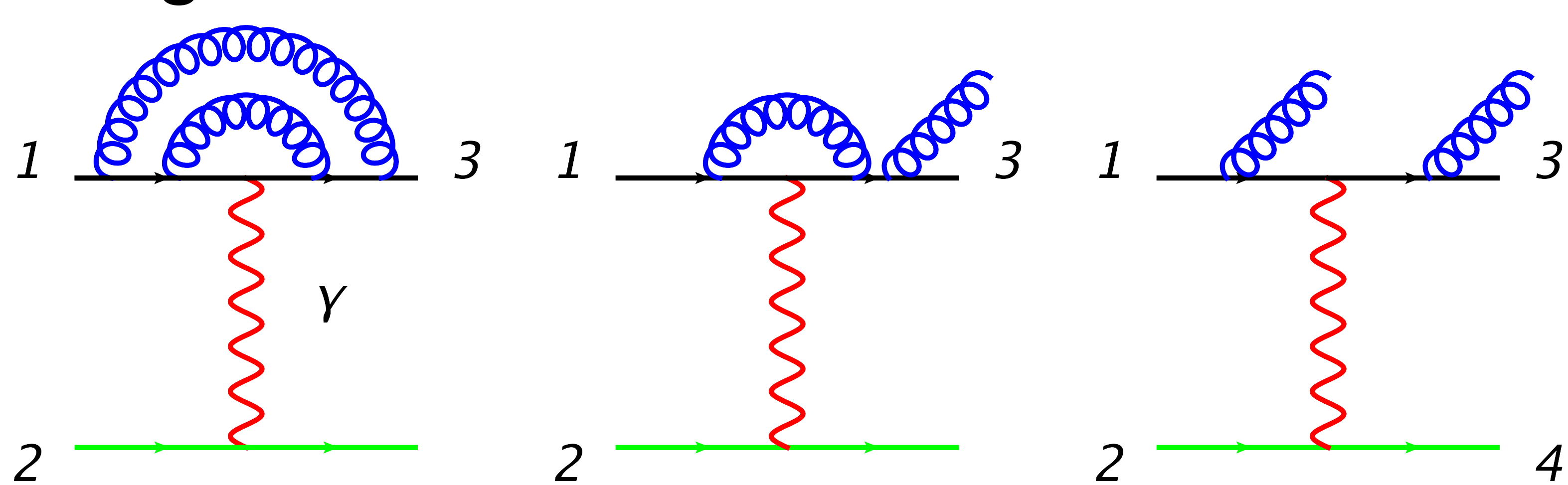
$$P_{\gamma l}(\xi) = \frac{1 + (1-\xi)^2}{\xi}$$

NNLO $O(\alpha^2\alpha_S^2)$ corrections

- New configuration: incoming lepton can split into a quark, leading to parton-parton scattering channels. They first appear at this order, and are therefore effectively leading order in our treatment.



- Standard NLO corrections to quark-photon scattering
- Double-virtual, real-virtual, and double-real corrections to quark-lepton scattering

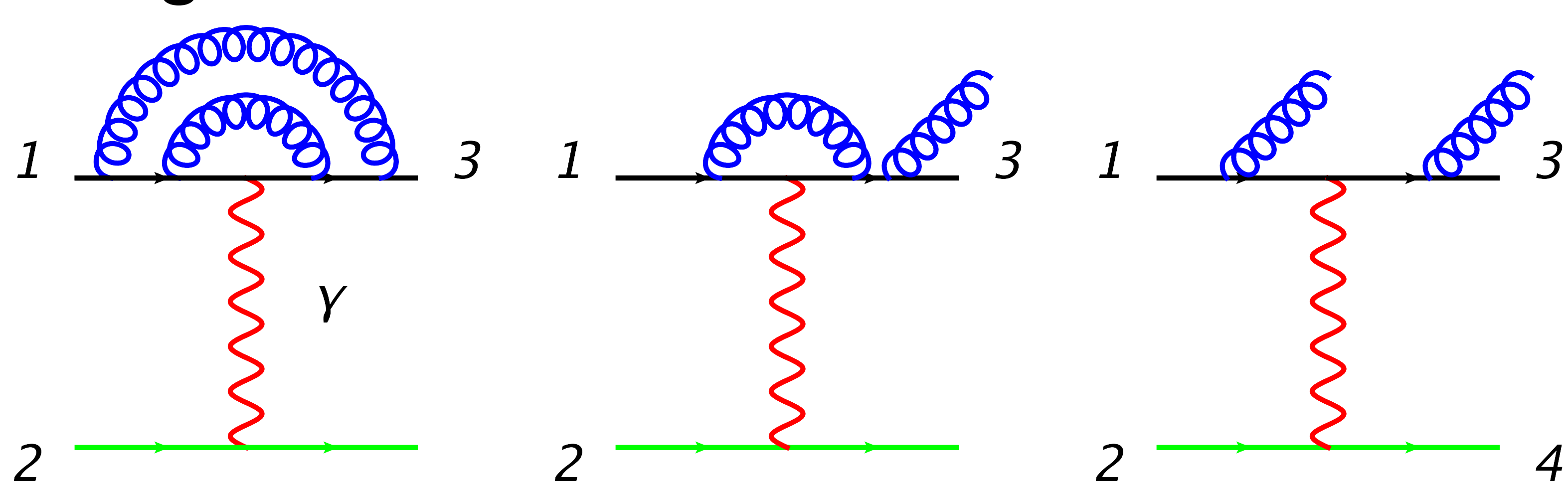


NNLO O($\alpha^2\alpha_S^2$) corrections

- New configuration: incoming lepton can split into a quark, leading to parton-parton scattering channels. They first appear at this order, and are therefore effectively leading order in our treatment.

All contributions separately divergent, with numerous singular configurations (triple-collinear, double-soft, soft+collinear, etc.) How do we regularize and cancel to arrive at a finite result?

- Stand
- Doub uark-lepton scattering



NNLO subtraction

Enormous progress solving this problem for LHC physics!

- First complete predictions for LHC V+jet, Higgs+jet production at NNLO; partial results for di-jet production
- N-jettiness subtraction: (Boughezal, Focke, Liu, FP (2015); Gaunt, Stahlhofen, Tackmann, Walsh (2015))

$$\mathcal{T}_1 = \frac{2}{Q^2}\sum_i \min\{p_B \cdot q_i, p_J \cdot q_i\}$$

Stewart, Tackmann, Waalewijn (2010);
D. Kang, Lee, Stewart (2013)

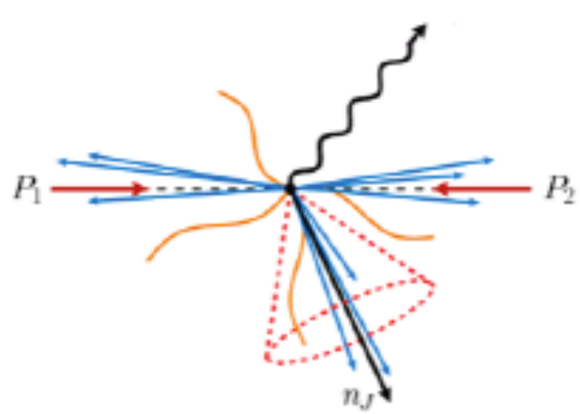
p_B: beam axis

p_J: leading-jet axis

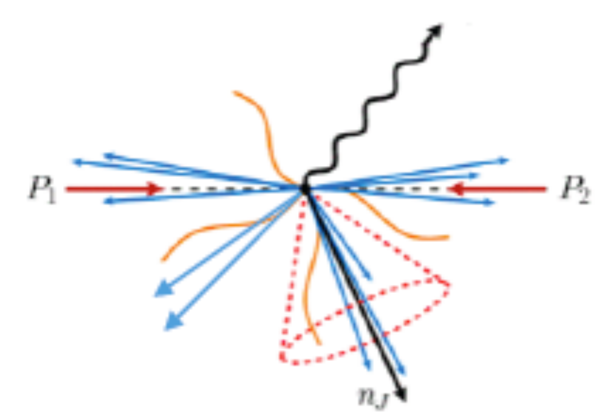
q_i: outgoing parton momenta

1 jet $\xleftarrow{\text{Small}}$ $\mathcal{T}_1$ $\xrightarrow{\text{Large}}$ At least 2 jets

Contributions from
- Two-loop
- Soft and collinear radiation



Contributions with at least 2 hard jets
- NLO two-jet calculation. Use known results/tools



N-jettiness subtraction

- N-jettiness can be applied to obtain exact NNLO cross sections
- Introduce τ_N^{cut} that separates the $\tau_N=0$ doubly-unresolved limit of phase space from the single-unresolved and hard regions

$$\begin{aligned}
\sigma_{NNLO} = & \int \mathrm{d}\Phi_N \, |\mathcal{M}_N|^2 + \int \mathrm{d}\Phi_{N+1} \, |\mathcal{M}_{N+1}|^2 \, \theta_N^< \\
& + \int \mathrm{d}\Phi_{N+2} \, |\mathcal{M}_{N+2}|^2 \, \theta_N^< + \int \mathrm{d}\Phi_{N+1} \, |\mathcal{M}_{N+1}|^2 \, \theta_N^> \\
& + \int \mathrm{d}\Phi_{N+2} \, |\mathcal{M}_{N+2}|^2 \, \theta_N^> \\
\equiv & \, \sigma_{NNLO}(\mathcal{T}_N < \mathcal{T}_N^{cut}) + \sigma_{NNLO}(\mathcal{T}_N > \mathcal{T}_N^{cut})
\end{aligned}$$

$$\theta_N^< = \theta(\tau_N^{cut} - \tau_N) \quad \text{and} \quad \theta_N^> = \theta(\tau_N - \tau_N^{cut})$$

N-jettiness subtraction

- For $\tau_N > \tau_N^{cut}$, at least one of the two additional radiations that appear at NNLO is resolved; this region of phase space contains the NLO correction to the N+1 jet process. **A solved problem!**
- For $\tau_N < \tau_N^{cut}$, both additional radiations are unresolved. A factorization theorem giving the all-orders result for small N-jettiness was derived

Stewart, Tackmann, Waalewijn 0910.0467

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_1} = \int \mathrm{d}\Phi_B \int \mathrm{d}t_J \mathrm{d}t_B \mathrm{d}k_S \, \delta\left(\mathcal{T}_1 - \frac{t_J}{Q^2} - \frac{t_B}{Q^2} - \frac{k_S}{Q}\right) \times \sum_q J_q(t_J,\mu)\, S(k_S,\mu) H_q(\Phi_2,\mu) B_q(t_B,x,\mu) + \ldots$$

H: describes hard radiation; in dim-reg, coincides with the 2-loop virtual corrections

B: describes radiation collinear to an initial-state beam

S: describes soft radiation

J: describes radiation collinear to a final-state jet

- The ellipses denote power corrections that become negligible for small τ_N^{cut}

Ingredients for the factorization theorem

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_1} = \int \mathrm{d}\Phi_B \int \mathrm{d}t_J \mathrm{d}t_B \mathrm{d}k_S \, \delta\left(\mathcal{T}_1 - \frac{t_J}{Q^2} - \frac{t_B}{Q^2} - \frac{k_S}{Q}\right)$$
$$\times \sum_q J_q(t_J,\mu)\, S(k_S,\mu) H_q(\Phi_2,\mu) B_q(t_B,x,\mu) + \ldots$$

- Expand this formula to $O(\alpha_S^2)$, and turn off all resummation, to get the NNLO cross section below the cut. Need each of these separate functions to NNLO.
- The beam and jet functions depend only on the flavor of the parton (quark, gluon); the soft function depends only on the parton flavors and the external hard directions; the hard function is the only process-dependent piece.

  - *H*@NNLO: Matsuura, van der Merck, van Nerven (1988)
  - *B*@NNLO: Gaunt, Stahlhofen, Tackmann (2014)
  - *S*@NNLO: Boughezal, Liu, FP (2015)
  - *J*@NNLO: Becher, Neubert (2006); Becher, Bell (2011)

Within the past two years all ingredients have become available to apply this idea to jet production at the EIC!

DISTRESS

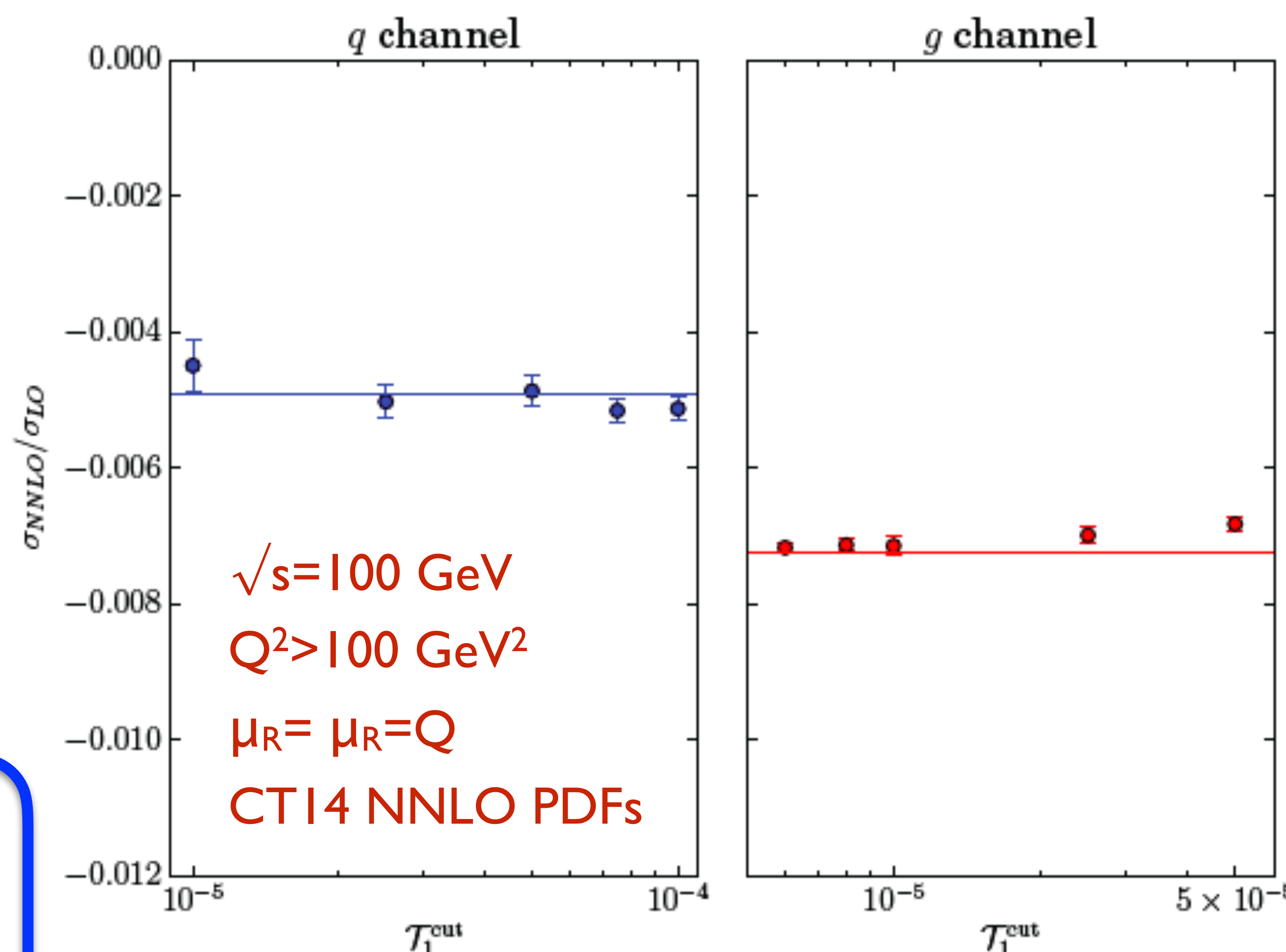
- **DISTRESS**: **DIS T**hrough a **R**obust **E**nabling **S**ubtraction **S**cheme

- Parton-level integrator for inclusive jet production in eN collisions
- Fully differential, allowing for arbitrary cuts on final-state jets/leptons
- Parallelized Monte Carlo integration
- Flexible framework allows for future extension to other processes (SIDIS, polarized collisions, …)

Validation

- We have two primary checks of our result at NNLO:

1. Independence of the full result from τ_1^{cut}; also determines when power corrections are negligible
2. Upon integration over final-state radiation, must reproduce inclusive structure function



Agreement with NNLO structure function

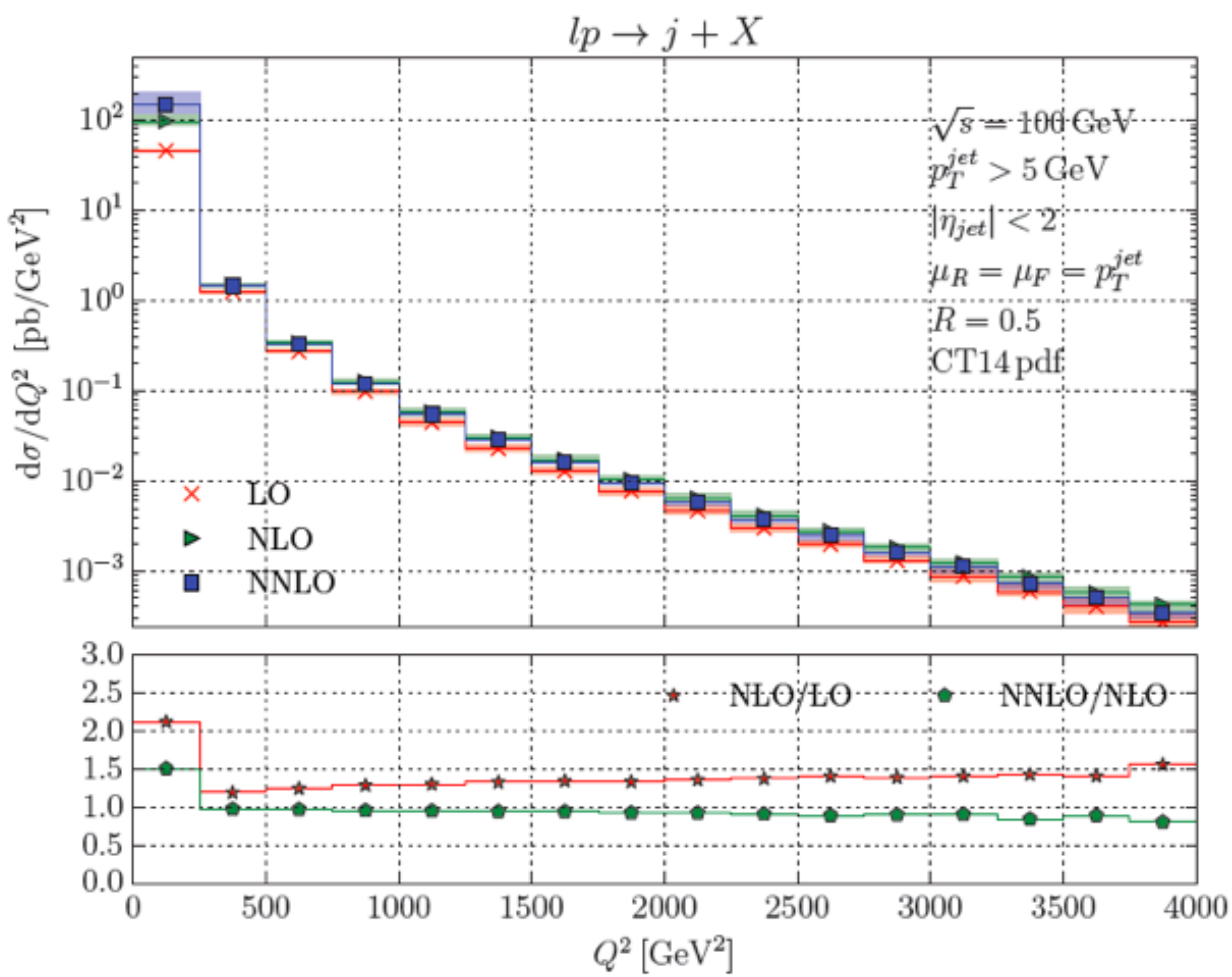
Zijlstra, van Neerven (1992); Moch, Vermaseren (1999)

Numerics: setup and Q^2 distribution

- Study the predictions from DISTRESS for possible future EIC parameters:

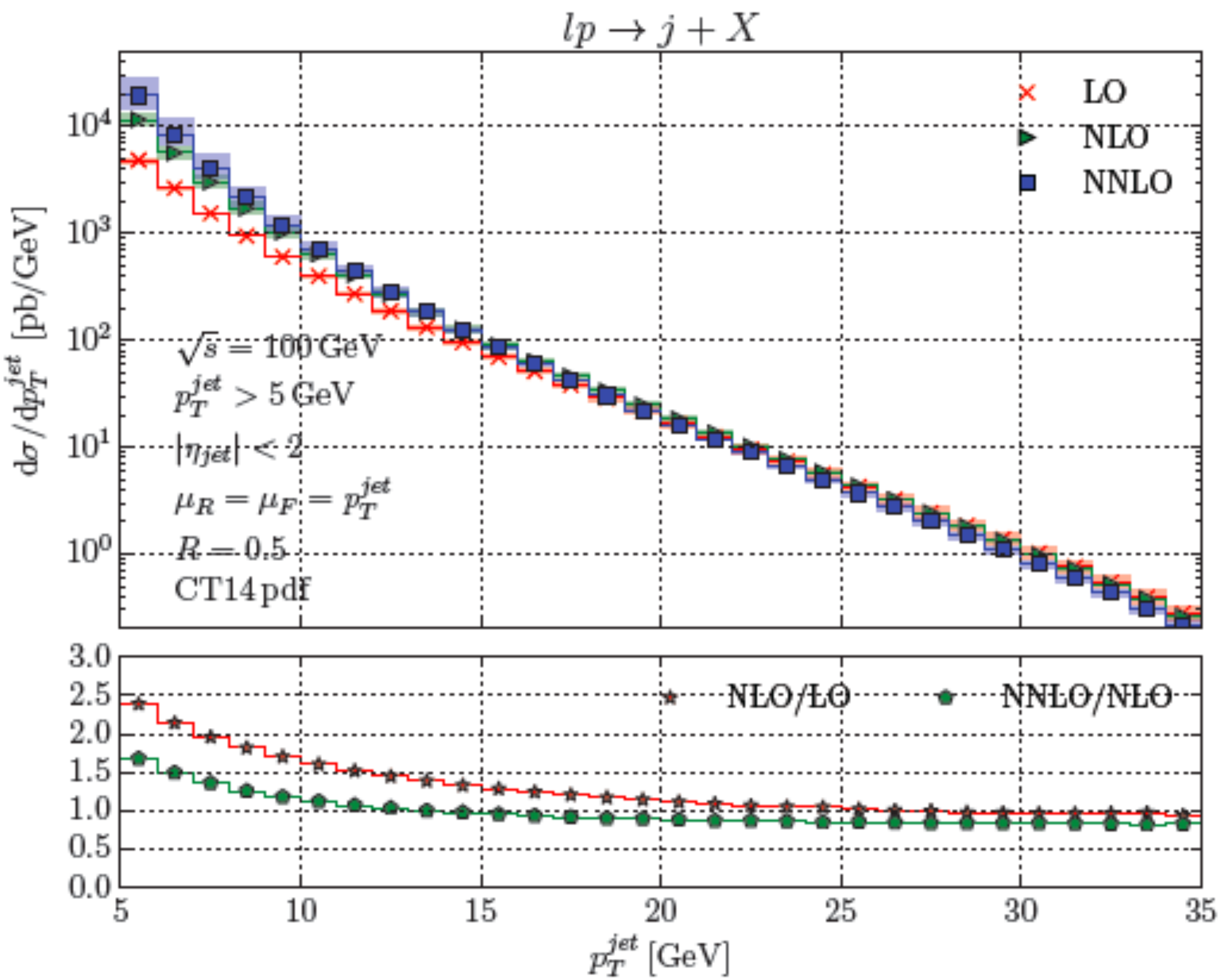
$\sqrt{s}$=100 GeV
p_{Tjet} >5 GeV
$|\eta_{jet}|$<2.0
Anti-k_T, R=0.5

$\mu_R=\mu_F=p_{Tjet}$
α=1/137.036
m_e=0.511 MeV
CT14 PDFs



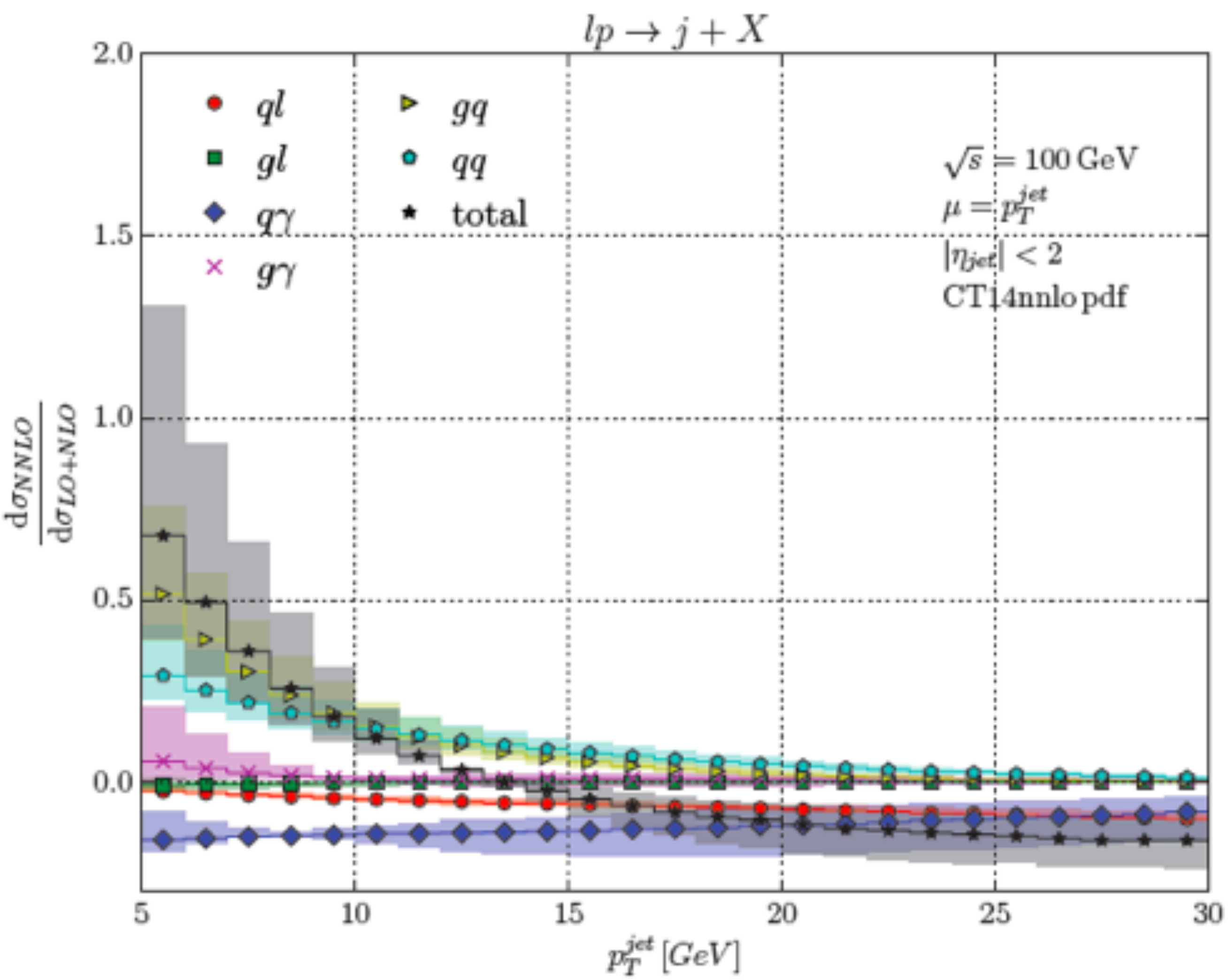
Large corrections at low Q^2 (photon-initiated processes)

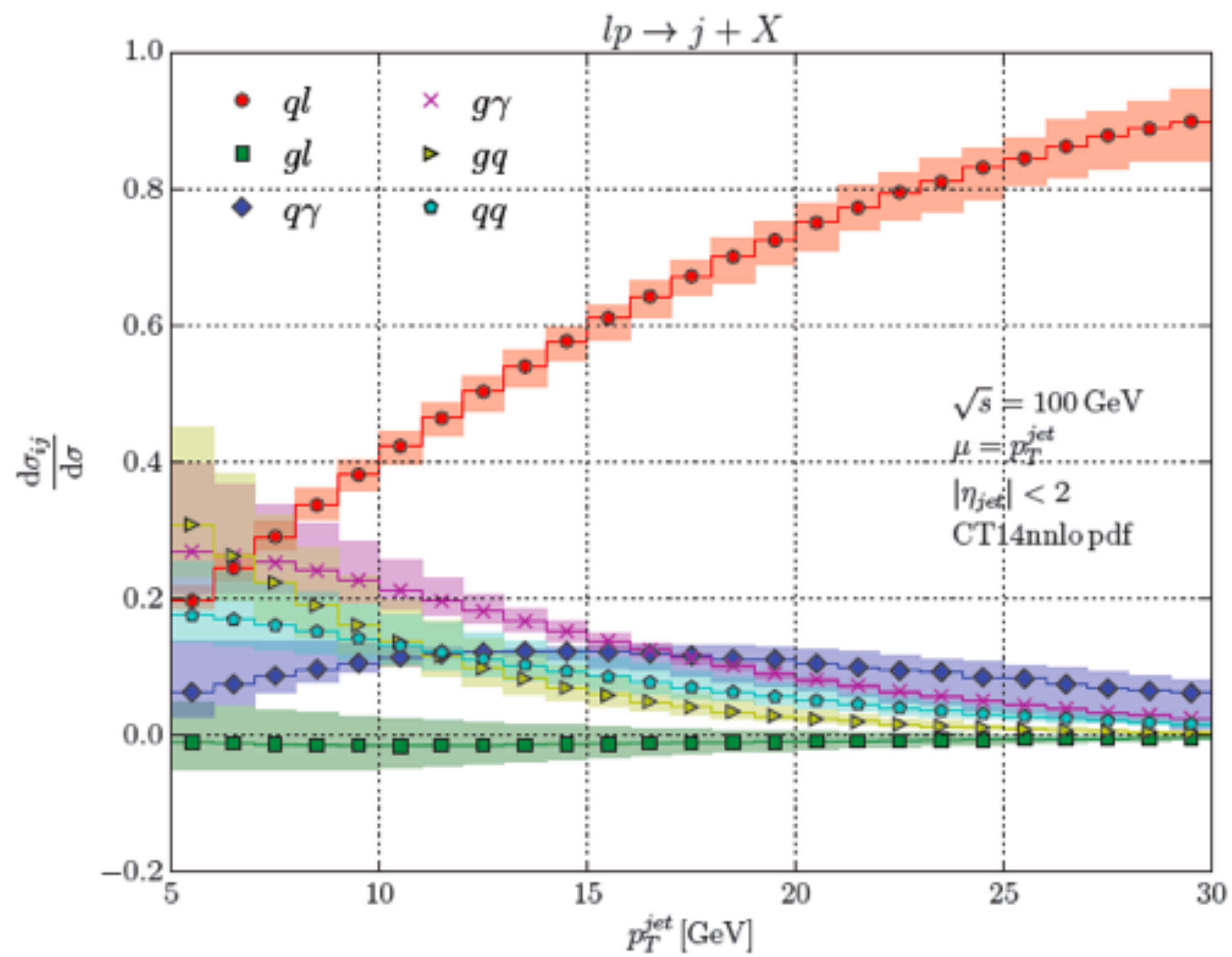
Numerics: p_{Tjet} distribution



- NNLO large and positive for p_{Tjet}<10 GeV; near unity for large momenta
- Scale dependence *increases* at NNLO for p_{Tjet}<10 GeV

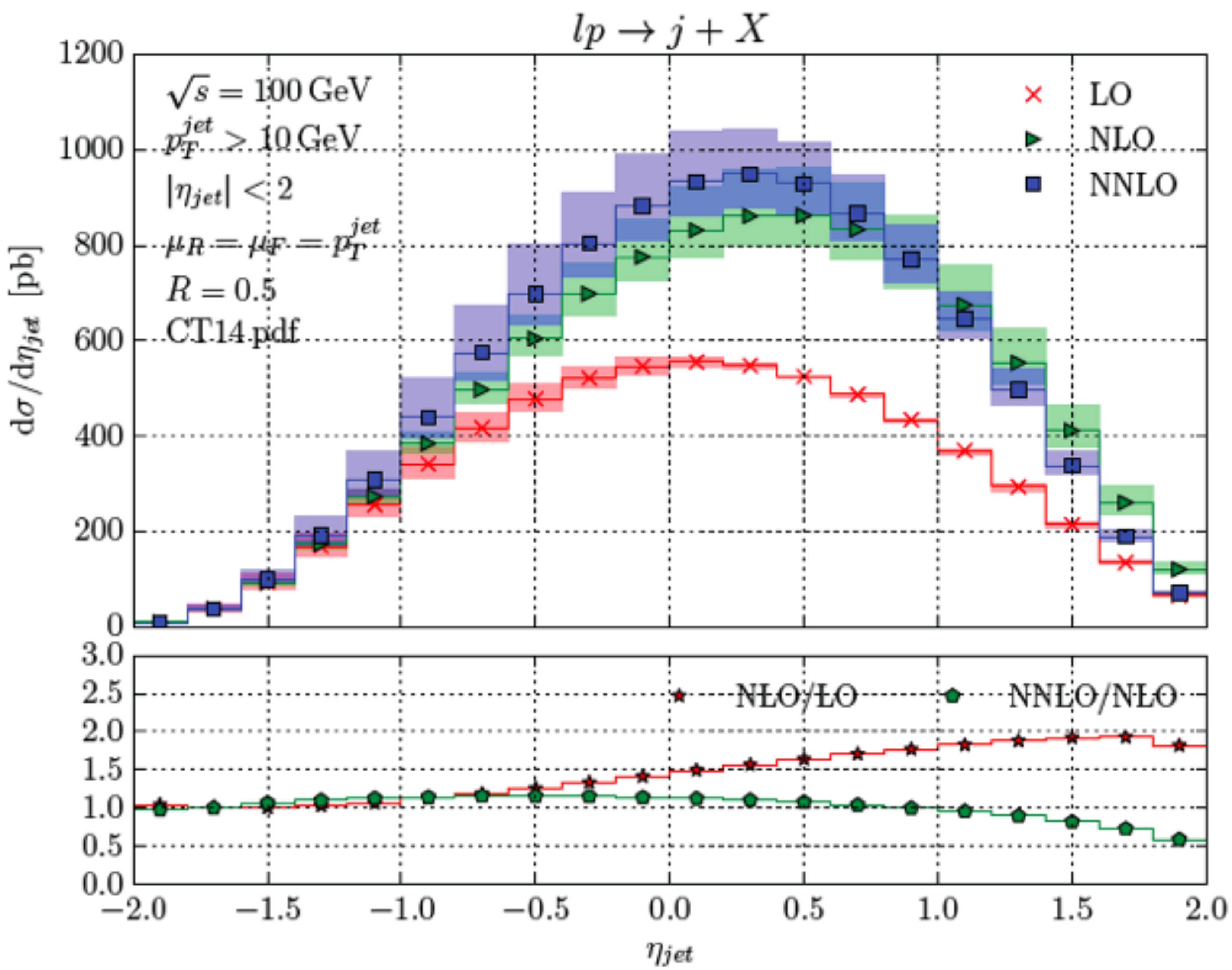
p_{Tjet} distribution: partonic channels





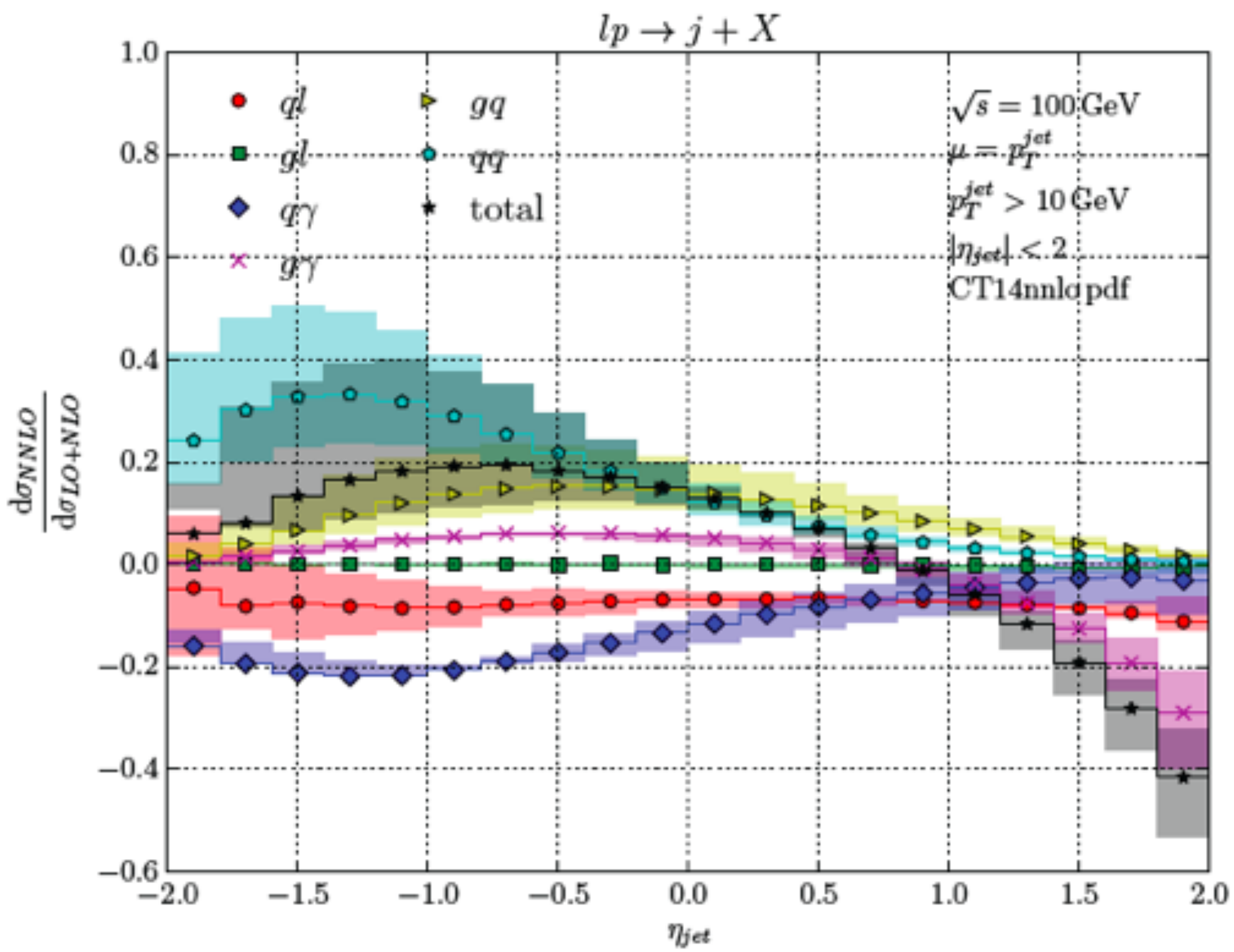
- qq and qg dominate the NNLO correction for low p_{Tjet}
- These channels begin at $O(\alpha^2\alpha_S^2)$, are effectively leading-order in this result, and drive the increased scale dependence at NNLO
- ql channel dominates for high p_{Tjet}
- No single channel furnishes a good approximation to the full result

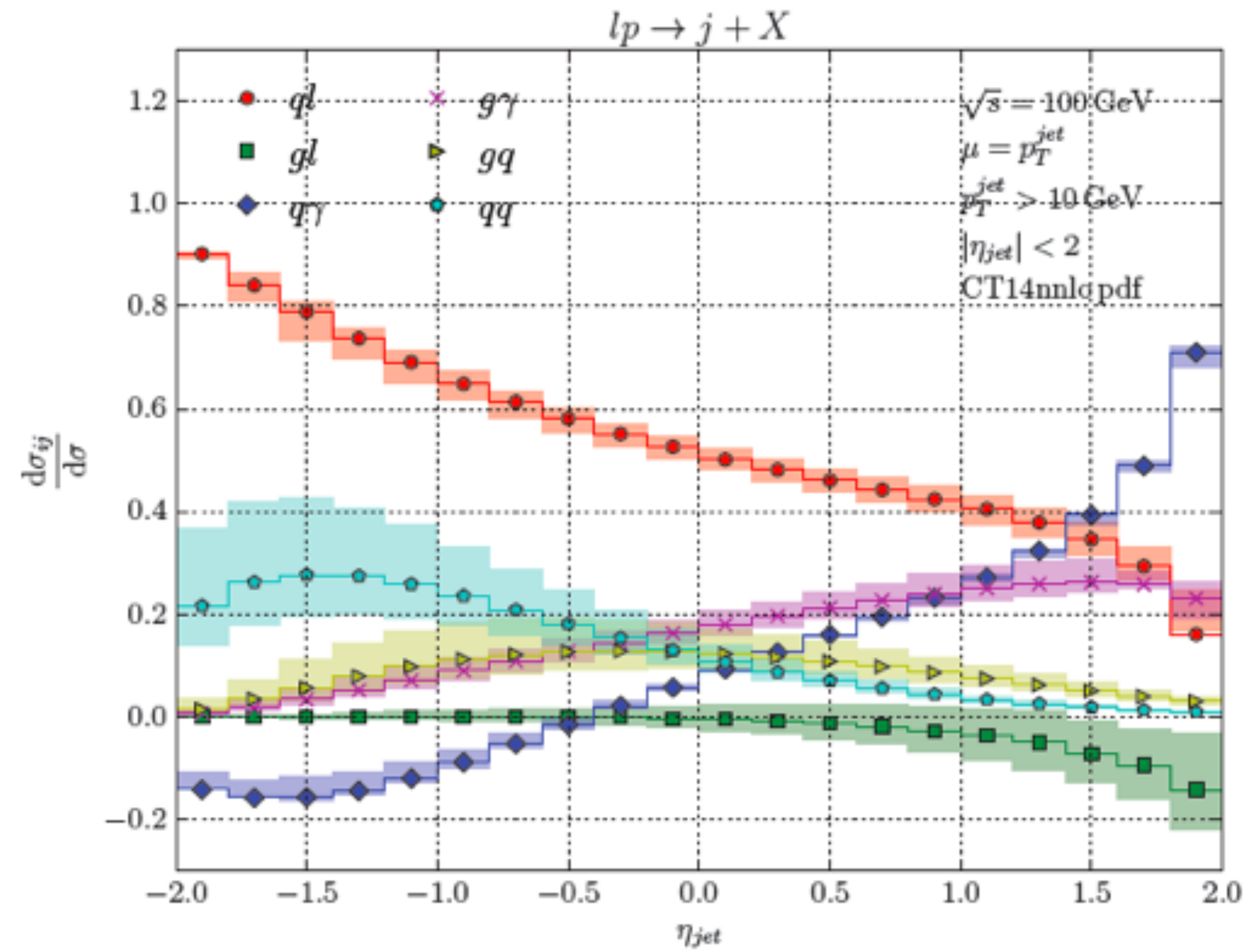
η_{jet} distribution



- NNLO corrections small for η_{jet}<1, but increase as $\eta_{jet} \to 2$
- Scale dependence *increases* at NNLO for η_{jet}<0

η_{jet} distribution: partonic channels





- qq channel drives the large scale uncertainty for $\eta_{jet}<0$; it begins at $O(\alpha^2\alpha_S^2)$, and is effectively leading-order in this result,
- ql channel dominates for low η_{jet}; $q\gamma$ channel dominates at high η_{jet}
- No single channel furnishes a good approximation to the full result

Conclusions

- We have presented a calculation of the full $O(\alpha^2\alpha_s^2)$ corrections to inclusive jet production at a future EIC
- Our calculation allows for arbitrary final state cuts as is implemented in the pardon-level program **DISTRESS**
- The magnitude of the corrections indicate that higher-order corrections will play an important role in the future EIC program
- Many additional EIC applications are possible using the techniques developed here; stay tuned!